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# EFFECTS OF NON-UNIFORM ENVIRONMENT DAMPING ON HAPTIC PERCEPTION AND PERFORMANCE OF AIMED MOVEMENTS

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## ABSTRACT

A set of experiments was conducted to investigate the relationship of environment damping to performance of a Fitts one-shot tapping task, and especially the relationship of environment damping to the haptic perception of target position. In the experiments, subjects were asked to locate a narrow target region that had a different level of viscous damping than the background regions. The task was performed using a one degree-of-freedom manipulandum. Movement time to target was measured as a function of the damping in the target and background regions. Different visual feedback conditions were also tested.

The most striking result of the experiments was that when the targets were *not* visible to subjects, performance was very closely correlated with the absolute magnitude of the difference in target and environment damping (i.e. target damping minus the background damping). Performance did not vary with the percentage difference between target damping and background damping, nor with the sign of the difference between target and background damping, nor with the level of background damping.

When target positions *were* visible to subjects, performance depended very weakly on the environment damping.

## 1 INTRODUCTION

### 1.1 Motivation

The performance of complex manipulation tasks such as surgery, sewing, carpentry, or auto repair relies a great deal on haptic perceptual information and requires carefully controlled and sometimes delicate mechanical interaction between the person and objects in the environment. Often the interaction is facilitated by the use of tools, which match human capabilities of mechanical energy delivery, to the mechanical requirements of the task. Interacting with the environment through a tool means that haptic perception of the environment is also via the tool, which may result in degradation or amplification of perceptions needed for the task at hand. The design of hand tools, including sophisticated tools such as telemanipulators (Hannaford, 1989, Hannaford and Fiorini, 1988, Hunter, et al., 1989, Raju, 1988), man-amplifiers (Kazerooni, 1990), and virtual environment interfaces (Adelstein and Rosen, 1992, Massie and Salisbury, 1994, Millman, et al., 1993, Minsky, et al., 1990) should reflect consideration of both aspects of tool use: human-environment mechanical interaction and human mechanical perception, or alternatively, the action requirements and perceptual requirements of the task.

The experiments presented herein were designed to investigate the perception of spatial variations in damping and the influence of the variations on performance and strategy. One aim was to answer questions of *perception* such as: What is the smallest damping non-uniformity that a person can detect? What sort of motions or exploratory procedures are used to detect these features? Is a target with greater viscous drag than the rest of the workspace easier to detect than a target with relatively less viscous drag? Another aim was to study how people exploit the mechanical constraints offered by the environment through *non-perceptual* means. One possible example is people relying on the braking action of highly damped targets (relative to the background) to help stop their motion.

### 1.2 Related psychophysics and perception studies

The following is a brief summary of related studies of haptic perception and the mechanoreceptors related to haptic perception.

The perception of limb position and motion seems to arise primarily from the spindle receptors in muscles and golgi tendon organs (Houk, et al., 1981, Hulliger, 1984, Mathews, 1988, McMahon, 1984). In arm positioning studies by Bahrick (1955) and Weiss (1954), subjects' absolute accuracy in positioning control sticks using arm motion degraded with larger movement amplitudes, but their accuracy relative to movement amplitude improved. Others, however, report a Weber fraction[1] for angular position of the forearm and hand as approximately 0.09 (Durlach, et al., 1989, Erickson, 1974) .

The sensation of muscular exertion seems to be via the efferent command from the CNS (Jones, 1986, McCloskey, 1981). Presumably this mechanism is used to perceive low frequency forces of interaction between actors and the environment, although cutaneous sensors are also likely to be important in many situations, especially those involving the hand. Various studies indicate that the Weber fraction for static force applied by the arm is 0.15 (Jones, 1989, Ross and Brodie, 1987), and the Weber fraction for force applied by the fingers is approximately 0.07 (Pang, et al., 1991).

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[1] Weber fraction is a measure of the differential threshold of detectability and is defined as the just-noticeable difference in stimulus intensity, divided by the magnitude of the reference stimulus.

Cutaneous sensors also play a role in the sensing of finger position (Clark and Horch, 1986, Ferrell and Smith, 1988), though they seem to be most important for sensing tactile stimulation such as pin pricks and vibrations. Howe and Kontarinis have demonstrated the importance of high frequency tactile feedback in teleoperation for perceiving small surface features and texture, and for performing dynamic tasks such as puncture and ball-bearing inspection (Howe and Cutkosky, 1993, Kontarinis and Howe, 1994).

The human capacity to perceive magnitude differences in linear environment impedances such as stiffness, damping, and moment of inertia has also been investigated. The reported Weber fraction for stiffness was 0.23 (Jones and Hunter, 1990) and for damping was 0.34, for viscosities greater than 20 N·s/m (Jones and Hunter, 1993). Differential thresholds for moment of inertia have been measured between 0.28 and 1.13 (Kreifeldt and Chuang, 1979, Ross and Benson, 1986).

The psychophysical experiments described thus far were primarily limited to measurements of low-level perception such as force discrimination and limb proprioception. Klatzky and Lederman have focused on higher level haptic perception, taking a more ecological approach in their experimental design. They conducted studies which show that although people have difficulty recognizing raised-line drawings of common objects using touch (Lederman, et al., 1990), they can easily recognize familiar three-dimensional objects such as pencils by touch (Klatzky, et al., 1985). Klatzky and Lederman proposed that "the haptic perceptual system makes use of stereotyped motor patterns", which they call *exploratory procedures*, to encode various object properties such as texture, hardness, weight, and shape (Klatzky, et al., 1989). Texture, hardness, and weight are each specified by the pattern of stimulation produced when objects are handled in a certain way.

A goal of our research in haptic perception is to identify different structures or features in mechanical environments that people can readily perceive. For tool use, handle motion (position and its derivatives) and force might be taken as the basic stimulus parameters which are structured in various ways (under certain conditions of motor exploration) to convey information about the environment and one's relation to the environment. And one can consider the *impedance* of the tool handle, i.e. the relation (not necessarily linear) of handle force to motion, as a description of the structure of the mechanical interaction between a person and the environment.

In our experiments, the variations in damping with handle position are features of the environment that provide information about target position. Other states of interest in tool use might include tightness of a bolt, depth of a chisel cut, or whether two parts are stuck or sliding.

## 2 EXPERIMENTS

### Experiment 1: Movement Task with Haptic Feedback Only

In the main experiment, subjects moved the handle of a one degree-of-freedom manipulandum from a starting position to a target position as quickly as possible. The *target position was not displayed visually*, however, the position of the manipulandum handle was visually displayed to subjects as a cursor on a computer monitor. The target zone comprised a narrow region in which the viscous drag on the handle, i.e. the damping, was different from the drag over the rest of the range of motion of the handle. Movement times were collected at various levels of damping in the target and surrounding regions.

#### Method

Subjects. Three male Northwestern University graduate students served as paid subjects. Subjects *A* and *B* were right-handed and subject *C* was left-handed. They had no known visual or motor deficits. Subjects were paid according to performance such that their hourly rate was approximately $5.50/hr.

Apparatus. The apparatus used to conduct the experiments was a one degree-of-freedom haptic display, shown in Figure 1. The system comprised a crank attached directly to the output shaft of a DC brushless motor (Electro-Craft model S-4075 and amplifier model DM30), an optical encoder (900,000 counts/rev.), a fluid-filled mechanical damper (custom design), and a PC-based digital controller (50 MHz, 486 IBM AT-compatible) running at 1000 Hz. The lever arm attached to the motor shaft was 0.152 m (6 inches) in length. Forces of up to 150 N (34 lbs) could be generated at the handle. D/A resolution was 12 bits.

The purpose of the mechanical damper between the drive shaft and ground was the improvement of system stability properties when simulating large magnitude impedances (Colgate and Brown, 1994, Colgate and Schenkel, 1994). The 40 N·s/m (approx.) of damping generated by this physical damper was compensated at low frequencies by measuring the reaction torque on the damper mount (i.e the damping torque) and feeding it back to the controller. The torque signal was then digitally filtered with a 4-pole modified Butterworth lowpass filter ($f_c$ = 10 Hz) and added to the commanded motor torque. The net effect is that the damper provides significant damping at high frequencies (improving stability) but very little damping at frequencies in the range of voluntary human motion (users do not feel the damping). The physical damping and torque feedback have no relation to the software-controlled experimental damping parameters and remained constant throughout the experiment.

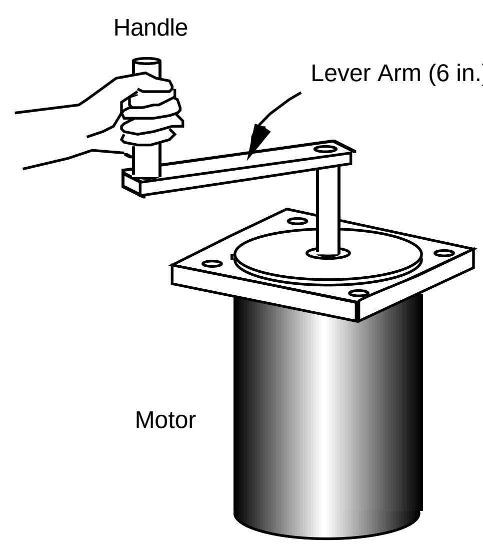


Figure 1(a). Sketch of one degree-of freedom "crank" manipulandum used in experiments.

FIGURE 1(b). One degree-of-freedom manipulandum used in experiments. Experimental setup with CRT display and subject grasping handle. In the actual experiments a shroud was in place that prevented subjects from seeing their hand or the handle.

The device was quite backdriveable. It is informally estimated that at low frequencies (below 10 Hz) the damping felt at the handle was 1.5–2.0 N·s/m. The inertia felt by subjects at the handle was approximately 0.35 kg and was primarily the mass of the handle itself. An experimentally obtained transfer function from commanded force to output force showed that the magnitude of the output force varied less than 10% from 0 to 100 Hz. The data were taken with the lever-arm and handle removed and a torque sensor attached between the top of the drive shaft and mechanical ground.

The computer generated a color graphical display of the experimental environment which prompted both subjects and experimenter with sounds, text and graphics during the experiments. The color monitor (14 inch, 640×480 pixels) was placed approximately 0.6 m in front of subjects with the center of the screen roughly 0.25 m below eye level. The manipulandum handle was 1.2 m from the ground, which was a comfortable height for all three subjects while standing.

A rigid shroud over the top of the mechanism (not shown in Figure 1), blocked the subject's view of his hand.

Linear damping at the handle was simulated using the relation

$$F = Bv \tag{1}$$

where $F$ is the handle force commanded to the motor, $v$ is the measured velocity of the handle, and $B$ is the virtual damping parameter. The velocity was estimated in the control algorithm from the encoder position signal using a first-order recursive digital differentiator plus lowpass filter, cutoff frequency 8 Hz.

Design. On the day prior to the first tests, each subject practiced for the three experiments in a 90-min session. Data for Experiment 1 was collected in three sessions over the next three consecutive days. The three sessions each lasted 120-150 min. During these sessions, 5-10 minute breaks were taken at least once every hour. There were 42 blocks of trials per session. Each block consisted of 4 warm-up trials and 9 test trials. The damping of the target and background regions was fixed during each block, and changed between blocks, so that 42 different damping conditions were tested during each session. The 42 blocks of trials were presented in a different random order to each subject. Before beginning each experimental session, subjects completed two blocks of trials (randomly selected from the set of 42) to become reacquainted with the testing procedure and warm up for the subsequent 42 blocks of test trials.

For all of the experiments, *ambient damping* ($B_{amb}$), was defined to be the virtual damping over the entire range of motion of the manipulandum *except* the target zone, and *damping difference* ($\Delta B$) was defined as the difference between the virtual damping in the target zone and the ambient damping, that is, target damping minus ambient damping (see Figure 2). In Experiment 1, three levels of ambient damping (0, 50, and 100 N·s/m) were tested. For each value of ambient damping, between 9 and 17 values of $\Delta B$ were tested. Their values ranged from –100 to +100 N·s/m except that no values of $\Delta B$ were used that resulted in net target damping less than zero. The absolute values of $\Delta B$ were logarithmically spaced along seven intervals between 0.5 and 100 N·s/m. The $\Delta B = 0$ case was also tested for each level of $B_{amb}$.

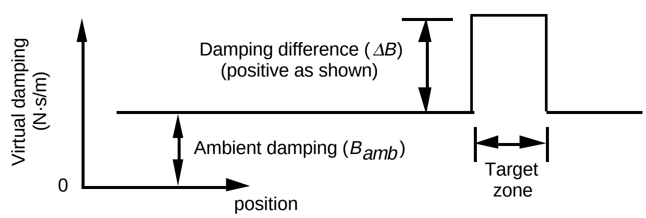


FIGURE 2. Virtual damping vs. handle position. The independent variables in all of the experiments were ambient damping ($B_{amb}$) and damping difference ($\Delta B$). In a block of trials, targets appeared once at each of nine discrete locations throughout the workspace. The order of appearance of these nine locations was random.

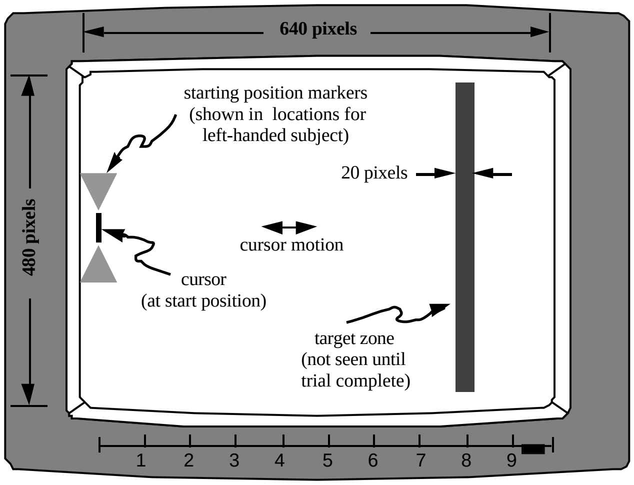


FIGURE 3. CRT display for Experiments 1, 2, and 3. Starting position markers and target zone shown in proper arrangement for left-handed subject.

Procedure. The procedure for the experiment was closely modeled on that of Meyer, et al. (Meyer, et al., 1988, Meyer, et al., 1990). Each trial started with an initial display on the computer monitor that included a starting position marker on one side of the screen and a movable cursor as depicted in Figure 3. The cursor was 1 pixel wide and 50 pixels in height. Rightward and leftward motion of the manipulandum handle produced respective rightward and leftward horizontal motion of the cursor. In the starting position, the manipulandum handle was pointing directly away from the monitor screen so that subjects' forearms were parallel with a sagittal plane. Right-handed subjects performed a right-to-left motion during their trials and left-handed subjects moved left-to-right. This resulted in a net pushing, rather than pulling motion of the handle.

On a particular trial, the target zone was centered at one of nine possible locations. In terms of handle motion, these locations were 2.5 cm apart, ranging from 2.5 cm to 22.5 cm from the starting position. The target zones were 0.85 cm wide (again in coordinates of handle motion). Movements to the most distant targets required approximately 90° of handle rotation. The mapping from handle motion, which was along an arc, to cursor motion, which was along a line, was quite natural to subjects.

The sequence for a single movement trial was as follows. The subject moved the cursor into the area on the screen between the two triangles that marked the starting position. The experimenter then pressed a button that enabled the motor amplifier, thereby "turning on" the haptic display. A haptic detent, simulated by a linear stiffness, held the handle accurately at the start position. Subjects were instructed not to push against the starting detent. Approximately, one-half to one second after the detent was activated, the experimenter pressed another button which initiated the automatic trial sequence. After this button was pressed, the start position markers changed color from red to yellow. A 1 s foreperiod ensued, followed by a series of three low tones and one high tone. The tones were 50 ms long each, separated by 260 ms of silence. After the last tone, the starting markers changed color to green and the starting detent was turned off. The high tone and the green color signaled the subject to initiate his movement to the target.

During subjects' movements, the cursor was always visible. Subjects were informed that the target was somewhere on the screen, but not in the area between the starting markers. The trial was finished when the following two criteria were continuously met for a period of 160 ms: (a) handle position was within the target range, and (b) handle velocity was less than 0.38 cm/s. The beginning of the 160 ms "hold period" was defined as the end of the movement. Successful completion of the trial was signaled by a high pitched tone, and the appearance on the screen of a colored band representing the target range. Subjects were allowed a maximum of 15 s to complete the trial. If the target was not reached after 15 s, a low tone sounded and the target band appeared on the screen.

The beginning of the movement, for the purpose of measuring movement time, was defined as the time at which the handle velocity exceeded 0.30 cm/s in the direction toward the target. If after 500 ms handle velocity had still not exceeded this threshold, the trial was stopped and rerun. Subjects were told that delays would not be included in their movement times, but that they should begin their movements shortly after the start signal.

Subjects were instructed to use whatever strategies of motion possible to find targets and to position the handle on the target as quickly as possible. They were allowed to adopt whatever posture, grip, and trajectory they liked for each different environment. At the end of each movement, the cursor stopped moving and remained fixed in its location at the end of the hold period. This allowed subjects to see where they were positioned relative to the target zone. The movement time was also displayed on the screen to provide feedback to subjects on their performance. After approximately 1 s, the experimenter pressed a key to disable the motor and reset the display for another trial. Subjects then signaled their readiness to begin the next trial by moving the cursor to the start markers, usually within 1–2 s after the motor was disabled.

Subjects were paid according to their performance.

## Results: Experiment 1

The results of Experiment 1 are shown in Figure 4. Average movement times for the three subjects are plotted versus damping difference ($\Delta B$) for each value of ambient damping. Each curve is for a different fixed value of ambient damping, and each data point represents the average of 27 test trials (9 trials × 3 days). At $\Delta B = 0$ the values of the three curves have been averaged and are represented on the plots by the solid horizontal lines. The special condition of a haptically "invisible" target (i.e. $\Delta B = 0$) was included in order to determine how long it took subjects on average to complete the search/positioning task by trial and error. Without visual or haptic information about target location, subjects could still oftentimes complete the task before the 15 s time limit by repeatedly moving the cursor to a new screen location, stopping, and waiting for the tone that signaled "target found".

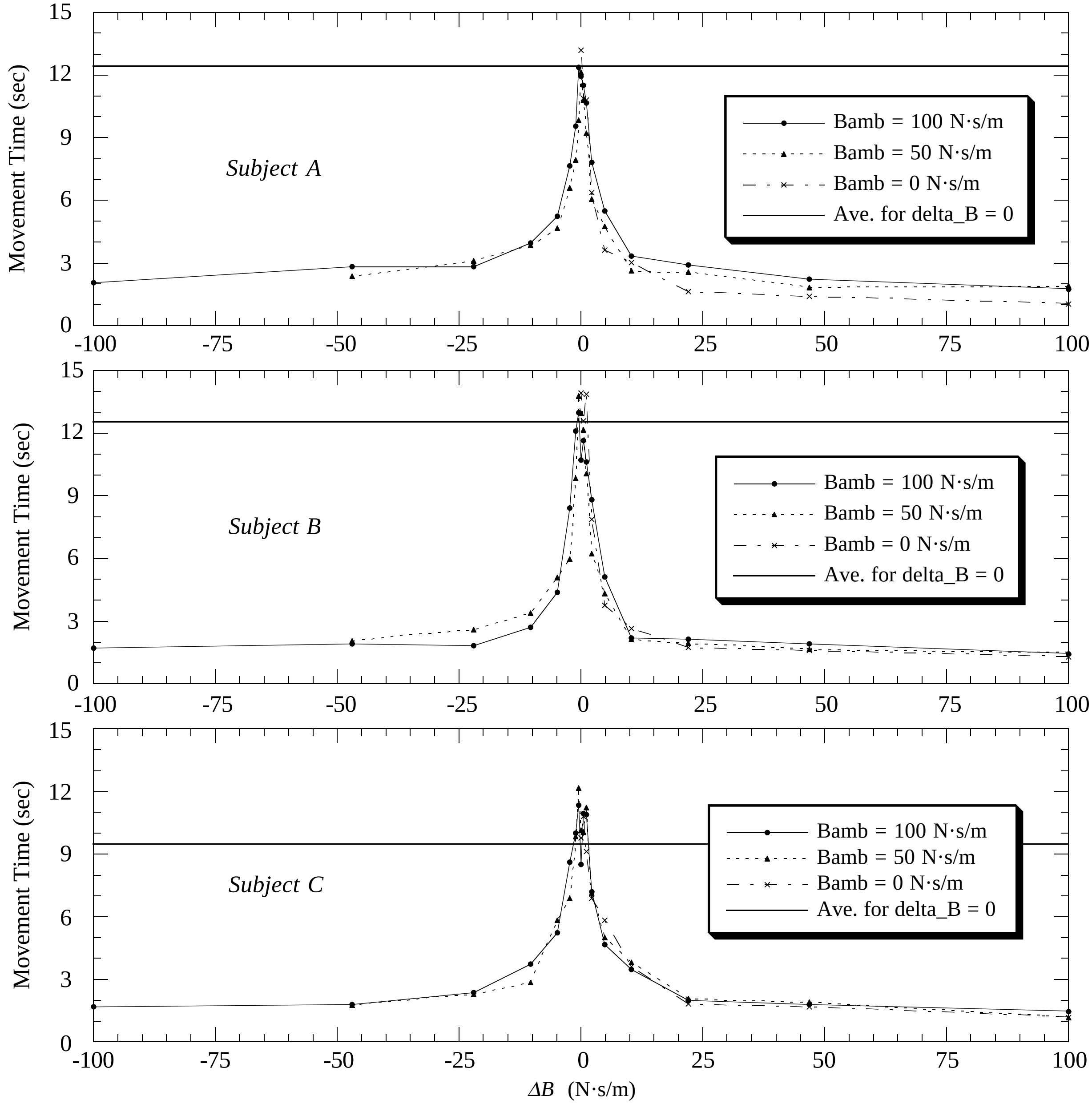


FIGURE 4. Average movement times for Experiment 1, Subjects *A*, *B*, and *C*. The three curves on each plot correspond to the three levels of ambient damping tested. Movement times are plotted versus $\Delta B$, the difference between target damping and ambient damping. The solid horizontal lines represent the average of the three curves at $\Delta B = 0$, the condition of non-perceptible targets.

TABLE I
RESULTS OF ANOVA TESTS FOR JUST-DETECTABLE DAMPING DIFFERENCE

| Test | Treatment groups (data for all three values of ambient damping grouped together) | Statistic (minimum for the 3 subjects) | Significance (maximum *p*-value for the 3 subjects) |
|---|---|---|---|
| 1 | $\lvert\Delta B\rvert$ = 0, 0.5 N·s/m | $F_{min}(1,214) = 0.4$ | $p_{max} > 0.10$ |
| 2 | $\lvert\Delta B\rvert$ = 0, 0.5, 1.1 N·s/m | $F_{min}(2,348) = 2.9$ | $p_{max} > 0.05$ |
| 3 | $\lvert\Delta B\rvert$ = 0, 0.5, 1.1, 2.3 N·s/m | $F_{min}(3,482) = 17.5$ | $p_{max} < 0.001$ |

One of the most noticeable features of the curves in Figure 4 is that the movement times show almost no dependence on ambient damping. An analysis of variance (ANOVA) test was performed at each value of $\Delta B$ to determine if the movement times for the three levels of ambient damping were significantly different.

Different levels of ambient damping did not result in significantly different movement times for any of the subjects (i.e. in each case $F(2,78) < F_{crit(\alpha=0.05)} = 4.0$), with the following exception. For $\Delta B$ = +22, +50 and +100 N·s/m, Subject *A*'s performance for $B_{amb} = 0$ was significantly better compared the two higher levels of ambient damping (i.e. in these cases $F(2,78) > 9.8$; $p < 0.001$). For these conditions, movement times for *Subject A* were 32-44% less when $B_{amb}$ = 0, compared to the combined average of the movement times when $B_{amb}$ = 50 and 100 N·s/m.

Another distinct feature of the data is the symmetry of the curves about the $\Delta B$ = 0 point on the x-axis. Movement time did not show a dependence on the *sign* of $\Delta B$ for the levels tested, with the exception of $\Delta B$ = ±100 N·s/m. Student's *t*-test assuming equal variances was used to compare sample means of two treatments, both having $B_{amb}$ = 100 N·s/m, and $\Delta B$'s of equal absolute value, but opposite sign.

The only significant differences found between treatments with damping differences of equal magnitude but opposite sign were those of $\Delta B$ = +100 and –100 N·s/m, for two of the three subjects ( $t(52)$ = –2.2 and –8.9; $p_{two\text{-}tailed}<0.05$). For all three subjects the average movement times for the maximally damped targets ($\Delta B$ = +100) were less than the movement times for the minimally damped targets ($\Delta B$ = –100 N·s/m) by 14-18%. It is somewhat surprising how large the magnitude of damping difference had to be for an asymmetry between positive and negative damping differences to be seen experimentally. Larger values of $\Delta B$ were not tested because feedback instability prevented the simulation of damping larger than 200 N·s/m.

Movement times for the smallest magnitudes of damping difference ($|\Delta B|$ = 0.5 and 1.1 N·s/m) were not significantly different from those of $\Delta B$ = 0 N·s/m. This hypothesis was tested using an ANOVA test in which the movement times for different absolute values of $\Delta B$ were compared. Since previous statistical tests showed that movement time was not dependent on the sign of the damping difference between target and background, nor on the value of the ambient damping, the data were grouped across these parameters. When the absolute value of the damping difference between target and background was 2.3 N·s/m or greater, movement times were significantly shorter for all three subjects than they were when the damping difference was 0 N·s/m. Movement times were on average 22-44% less for tests in which the absolute value of the damping difference was 2.3 N·s/m, compared to tests in which the damping difference was zero. Table I summarizes the results of the statistical tests which indicate that 2.3 N·s/m was the minimum difference in damping required for consistent haptic detection of targets by all three subjects.

It should be noted that the limit of 15 seconds imposed on subjects' movement times produced a non-normal distribution of the data, which compromises the precision of the statistical tests employed. Use of non-parametric statistical tests could address this problem. The conclusions made using the ANOVA test are, however, corroborated by observations of histogram data and from subjects verbal reports about which targets they could feel.

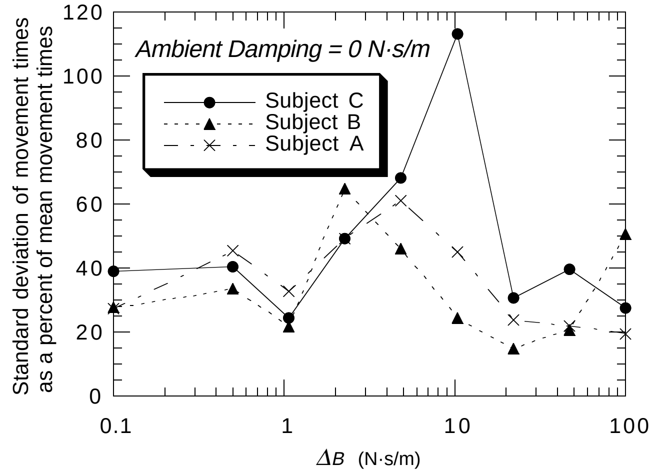


FIGURE 5. Standard deviations of movement times (normalized by mean movement times) vs. damping difference. Cases shown are for ambient damping equals zero.

The standard deviations of movement time versus $\Delta B$ for $B_{amb}$ = 0 N·s/m are shown for all three subjects in Figure 5 (data shown are merely exemplary). The values are normalized by average movement time. These normalized values are fairly constant with respect to $\Delta B$, and are generally between 20-60% of mean movement time.

Figures 4 and 5 show that the results of Experiment 1 are very similar across subjects, in terms of both absolute magnitudes and general trends.

### Experiment 2: Movement Task with Haptic Plus Visual Feedback

In another experiment, visual feedback of target position was provided, in the form of a colored band that appeared on the computer screen immediately after the signal to begin a movement was given. The purpose of the experiment was to make two comparisons of task performance: 1) haptic feedback alone vs. visual feedback alone, and 2) haptic feedback alone vs. haptic plus visual feedback.

Since target location was not visible until the start of each trial, subjects had virtually no time to preplan their movements. More precisely, the maximum time available for preplanning a movement, was 0.5 s, the allowed latency period before the onset of motion.

As in Experiment 1, three values of ambient damping (0, 50, and 100 N·s/m) were tested. The ranges of $\Delta B$ tested were also the same as in the first experiment, however far fewer intermediate values were included. The procedure, subjects and apparatus for Experiment 2 were identical to those of Experiment 1.

### Results: Experiment 2

Comparison of the average movement times for Experiment 2 with those from Experiment 1 indicates that over almost the entire range of damping differences ($\Delta B$), movement times were dramatically shorter if the target was visible (see Figures 4 and 6). At the extreme positive and negative values of $\Delta B$, however, targets were found almost as rapidly when they were invisible as when they were visible. The average movement time obtained with visual feedback alone (Exp. 2, $B_{amb}$ = 0, $\Delta B$ = 0) was 11-27% less than the average movement time for the best haptic feedback alone case (Exp. 1, $B_{amb}$ = 0, $\Delta B$ = +100 N·s/m). The difference was significant for all three subjects at $p < 0.05$ (two-tailed *t*-test).

Just as in Experiment 1, ambient damping ($B_{amb}$) had no statistically significant effect on performance (ANOVA on treatments with equal $\Delta B$), however some variation in movement time with $\Delta B$ was observed. Movement times generally decreased as $\Delta B$ increased. The shortest average movement time for any subject was 0.67 s, and the largest was 1.14 s.

Movement times for $\Delta B$ = +100 N·s/m ($B_{amb}$ = 100 N·s/m) were 22-29% shorter than those for $\Delta B$ = –100 N·s/m. These differences were significant at $p < 0.001$ (one-tailed *t*-test). The differences in movement times between $\Delta B$ = 0 and $\Delta B$ = +100 N·s/m, however, were not consistently significant to $p <$ 0.05 for all three subjects, though the average movement times were less for $\Delta B$ = +100 in all cases. The standard deviations of movement times from the mean were between 0.16 and 0.39 s, with most around 0.2 s.

The results of Experiment 3 indicate that the variations in environment damping did affect performance of the aimed-movement task even when target location was visible, though the effects were, of course, less marked than when target location could only be perceived haptically.

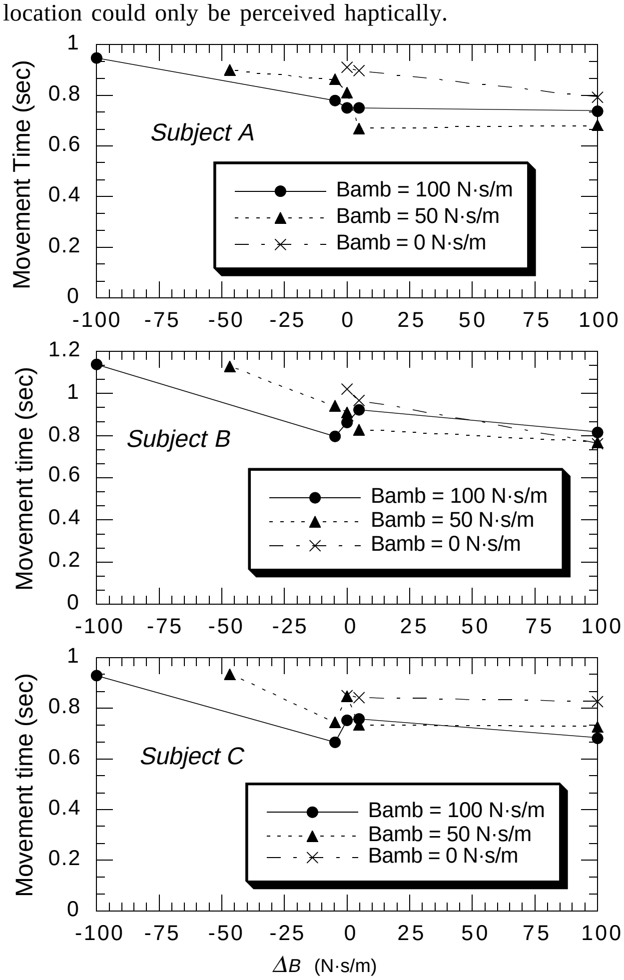


FIGURE 6. Average movement times for Experiment 2, positioning with visual feedback of target position, for all three subjects.

## 3 DISCUSSION

In this section, the strategies employed by subjects will be discussed in some detail, along with observations by subjects about the experiments.

The procedure used by subjects to perform the positioning task haptically, without visual information about target position, varied according to the magnitude of difference in damping between target and background ($\Delta B$). Subjects reported that for small $\Delta B$ they could not tell where the target was except by moving quickly over it. For difficult-to-feel targets, subjects swept the cursor across the screen, sometimes moving with large, rapid back-and-forth motions, other times with long, smooth sweeping gestures. Sometimes the two edges of the target could be felt, but often only one "thing" was perceived (at high velocities, the handle passed through the target in only 5-10ms). In fact, two subjects reported a frustrating phenomenon that for certain environments, they had a difficult time locating the two distinct edges of the target and that they repeatedly mistook the position of the target to be, for instance, to the right of where the target actually was.

For large magnitudes of $\Delta B$, one motion across the search range was enough to reliably and positively locate the target. An exploratory motion did not appear as a distinct movement, but was well incorporated into the execution of the task itself. This is, of course, very desirable for saving time and energy. Additionally, in the event that subjects needed to make minor corrective movements, they could perceive whether or not the handle was in the target range without traversing a target edge. Small motions or oscillations were enough to perceive this.

For environments with the largest positive damping difference ($\Delta B$ = +100 N·s/m), the main strategy used by subjects was to move the cursor rapidly across the screen, which usually carried them through the target on the first pass. Subjects then reversed their direction and moved back toward the target, pushing more lightly and often holding the handle more loosely so that when the target was hit again, the high damping in that region would bring the handle to a stop, without the subject applying a decelerating force. This proved to be a reliable and easy way to accomplish the task.

Targets with the largest negative damping difference ($\Delta B$ = –100 N·s/m) were also easy to find, though somewhat more difficult to stop in. As might be expected, subjects found that they tended to overshoot the target zone because as they entered it, they were pushing hard to overcome the large ambient damping, and then the resistance to their motion suddenly dropped. However, when they reached the opposite side of the target, the large ambient damping acted as a brake to keep them from overshooting by far. Subjects described the perception of an indentation that acted to hold them in the target, though they also said that the edges of the target zone were "sticky".

For damping bumps and indentations of more modest size, subjects found it necessary to actively sweep the handle across the search space, as described above. For the smaller values of $\Delta B$, subjects could only get an approximate sense of the target's location, so they would then begin a trial and error search for the target in the general area where the target was thought to be. If this was not successful within a short period of time, subjects might repeat their sweeping exploratory procedure to relocate the target. For altogether imperceptible targets, subjects would often immediately commence a trial-and-error search of the entire screen for the target.

An interesting feature of some of the data is that the movement times for $\Delta B = 0$ are somewhat shorter than those for $\Delta B = 0.5$ and 1.1 N·s/m. An explanation of this is that subjects seemed to sometimes have vague perceptions of these very small targets, so they spent time exploring the environment for the target before giving up and searching by trial and error. Whereas when there was no damping non-uniformity ($\Delta B = 0$), the fact that they could not feel a target was more clear to them, so they did not waste time attempting to feel it.

Another observation was that small non-uniformities were easier to feel when pulling the handle rather than pushing the handle. Also, one subject found small non-uniformities easier to detect when gripping the handle tightly, while another reported just the opposite, that a light grip was better.

The results of Experiment 2 showed only small differences in movement times for different values of environment damping. Subjects did report, however, that low to moderate ambient damping combined with very large target damping was the easiest environment. For these parameter values, the task could be performed without much mental effort or concentration. "You don't have to think, you just push", was one remark.

The most difficult environment for the visible-target experiment, according to two subjects, was ambient and target damping both very small. Their perception of difficulty contradicts the movement time results, which were consistently larger for $\Delta B = -50$ N·s/m and –100 N·s/m than for $\Delta B = 0$. All of these reports suggest that adding haptic cues to an interface can reduce attentional demands and free visual attention for other uses.

One of the results of Experiment 1 was that the smallest perceptible damping difference was around $|\Delta B| = 2.3$ N·s/m. Below this value, the force transients associated with traversing the targets are masked by system noise. High frequency (~110 Hz) humming of the motor is the largest contribution to noise. It is expected that with less massive, more refined machines, smaller differences in damping could be perceived. Experiments like these could even be used to establish benchmarks for comparing the "impedance noise" levels of different haptic interfaces.

## 4 CONCLUSIONS

The preceding discussion of the experiments and their results suggests that perceptual information influences performance of this task much more than the energetics of the task, or the mechanical constraints of the environment. For this task, subjects could compensate almost completely for any deleterious influence of the mechanics of the environment (e.g. large ambient damping), as long as they knew where the target was.

Perhaps the most surprising result of this study is that performance did not vary with the percentage difference between target damping and background damping, nor with the sign of the difference between target and background damping, nor with the level of background damping. The results, therefore, cannot be explained in terms of a Weber fraction of target and background damping. The target was just as easily perceived in an environment consisting of, for example, ambient damping = 100 N·s/m and target damping = 103 N·s/m, as in an environment of ambient damping = 0 N·s/m and target damping = 3 N·s/m.

This result shouldn't surprise us if we think of the task as a high-frequency feature detection task, not a damping discrimination task or a static force discrimination task. Perceptually the task seems to involve detecting sudden changes in handle resistance, or rapid force and acceleration transients. *Detectability* and *signal-detection theory* are, in the authors opinion, more suggestive paradigms for examining the results of the experiments (Egan, 1975, Gescheider, 1985, Green and Swets, 1966).

It is hypothesized that subjects scanned for high frequency force transients (i.e. higher frequencies than their own changes in velocity would produce in response to constant damping) of greater magnitude than the system noise. In haptic perception, the difference between discriminating two isolated patches of damping (Jones and Hunter, 1993), and detecting a damping non-uniformity in a single environment, is analogous to the difference in visual perception between discriminating between colors shown one after the other, and detecting the difference between two patches of color that are juxtaposed. In both modalities, artifacts of the spatial and temporal relationships of the stimuli (e.g. edges) play an important role in perception.

The importance of non-linearities in the environment impedance for haptic perception is twofold. The power spectrum of the voluntary motion input by the human is severely bandwidth limited, however a non-linear impedance can produce high frequency mechanical energy from the low frequency inputs by the human, thereby taking advantage of the sensitivity of the cutaneous sensors to high frequencies. Also, non-linearities provide the spatial and temporal specificity of stimulus patterns that seem to be important for perception.

In future experiments, the authors will investigate other types of impedances and other shapes of non-linearities.

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